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# Research on FCS-MPC for LC filter inverter

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***Abstract:*** *In the analysis of this paper, the main aim is to propose a finite control set model to implement the prediction, which is simpler for the control of LC filter inverters. During the analysis, the corresponding voltage and current equations in the phase coordinate system and the DC side neutral point voltage control equations are constructed. In, the forward difference formula is used to establish the model predictive control equations. It provides support for the FCS-MPC in the future.*

***Keywords:*** *LC filter inverter, Finite control set model, DC side neutral point voltage, Current*

## 1. Introduction

The demand for renewable energy is increasing rapidly because non-renewable resource are steadily being exhausted, so the renewable and clean energy sources has attracted world-wide attention. The significance of distributed generation systems for the use of renewable energy is recognized by the industry. As the core of distributed generation system, inverter makes it possible for renewable energy generation (such as photovoltaic power generation, wind power generation, etc.) and grid or load, and its performance directly affects the whole distributed generation system [1]. Traditional grid-connected inverters typically use the current source control in Pulse Width Modulation (PWM) technology [2], which leads to a large number of high-order harmonics in the grid current entering the grid, causing huge disturbance to the grid. Therefore, the grid-connected inverter must have an extremely high output power factor (PF), and the total harmonic distortion ratio (THD) of the output current in line with the national standard (GB /T 14549-1993) is less than 5%. In order to reduce the harm caused by reactive power, harmonics and other factors on the public power grid (PCC) [3]. Higher harmonics in the inverter output require low-pass filters. Design objectives include that the output voltage detuning content is small, and small filter parameters and size, and the resistance characteristic of the filter is excellent, and the power consumption of the filtering system is minor. Common inverter passive filters include L/LC/LCL. The L filter is a first-order system and does not achieve excellent results in filtering peak-order harmonics. The LCL filter increases the system order to the third order, which increases the control difficulty and reduces the system stability, and its volume is also large [4].

Therefore, this paper proposes a control system based on LC filters to improve the safety and effectiveness of inverter output.

At present, there are numerous main inverter control methods, including PI control, resonant control, hysteresis control, etc.In recent years, the performance of inverter has been significantly improved by current prediction, power prediction and prediction in model predictive control method. In recent years, the research of model predictive control with limited control set (FCS-MPC) algorithm in this field has also attracted the attention of various scholars. FCS-MPC takes full advantage of the distortion characteristics of power electronics converters. Considering the limited switching states of power electronics converters (converters with specific kinds of switch combinations), a cost function is used to evaluate the prediction results of each behavior (switch combinations). Choosing the switch combination that can satisfy the minimum cost function to realize the control of the power electronic converter also has the advantage of not using a modulator. This paper presents a finite control set model predictive control system for grid-connected inverter based on LC filter.

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## 2. Conventional LC filter type grid-connected inverter FCS-MPC

### *2.1 Mathematical model of LC filter type grid-connected inverter*

Figure 1 shows a block diagram of a typical LC filter grid-connected inverter topology and a grid-connected inverter for voltage prediction control. In the figure: $u^*_{gabc}$ is the given reference value of grid-connected voltage of the inverter. $S_{abc}$ is the state signal of the three-phase bridge arm switching device. Its value of 1 indicates that the switch is on, and its value of 0 indicates that the switch is off. $u_{dc}$ is DC voltage. $u_{abc}$ and $i_{fabc}$ are the output voltage and current of the inverter, respectively. $i_{gabc}$ is the grid-connected current. $R_g$ and $L_g$ are grid-connected resistance and inductance, respectively. $e_{abc}$ is the grid voltage. $u_{gabc}$ is the grid-connected voltage of inverter. The LC filter consists of a filter inductor L and a filter capacitor C on the inverter side, where $R$ and $R1$ are the parasitic resistances on the filter inductor and filter capacitor, respectively.

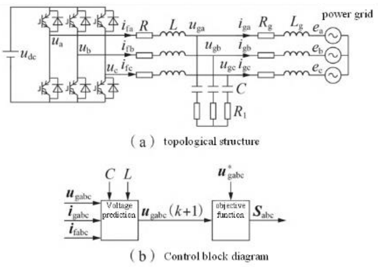


*Figure 1 Grid-connected inverter topology and control block diagram for LC filter type*

The mathematical model of LC filter grid-connected inverter in αβ coordinate system can be expressed as follows.

$$\begin{cases} L\dfrac{di_{f\alpha\beta}}{dt} = u_{\alpha\beta} - Ri_{fu_{g\alpha\beta}} - u_{g\alpha\beta} \\ C\dfrac{du_{g\alpha\beta}}{dt} = i_{C\alpha\beta} = i_{f\alpha\beta} - i_{g\alpha\beta} \end{cases} \tag{1}$$

Where, $i_{f\alpha\beta}$ and $u_{g\alpha\beta}$ are the inverter side output current and the inverter grid-connected voltage in the αβ coordinate system, respectively. $i_{g\alpha\beta}$ and $i_{C\alpha\beta}$ are the grid-connected current and filter capacitor current in the αβ coordinate system, respectively. $u_{\alpha\beta}$ is the inverter output voltage.

The discretization equations at time $k$ and $k$+1 in the αβ coordinate system can be further pushed by the forward Euler discretization method, as shown in Equation (2).

$$\begin{cases} \frac{L}{T}(\mathrm{i}_{f\alpha\beta}(k+1) - \mathrm{i}_{f\alpha\beta}(k)) = \mathrm{u}_{\alpha\beta}(k) - \mathrm{R}\mathrm{i}_{f\alpha\beta}(k) - \mathrm{u}_{g\alpha\beta}(k) \\ \frac{C}{T}\left(u_{g\alpha\beta}(k+1)\right) - u_{g\alpha\beta}(k) = i_{f\alpha\beta}(k+1) - i_{g\alpha\beta}(k) \end{cases} \tag{2}$$

Where: T is the sampling period. Considering that the inverter has eight different switching states, the eight voltage vectors $V_0$-$V_7$ can be generated accordingly. When performing the FCS-MPC method, it is generally necessary to substitute the switching states corresponding to these eight voltage vectors into the discrete equation of the prediction model shown in equation (2), so that the inverter grid-connected voltage $u_{g\alpha\beta}$ ($k$+1) at time $k$+1 can be predicted. Finally, the predicted grid-connected voltages of the eight inverters are substituted into the objective function G shown in equation (3), and the voltage that minimizes the objective function is selected as the optimal vector through comparative optimization.

$$G=| u^*_{g\alpha\beta}-u_{g\alpha\beta}(k+1) | \tag{3}$$

Where: $u^*_{g\alpha\beta}$ is the reference value of the grid-connected voltage of the inverter in the αβ coordinate system.

### *2.2 Principle of FCS-MPC*

In the past decade, with the improvement of the data processing ability of microprocessors, the application of FCS-MPC in the field of power electronics has achieved rapid development and attracted more and more attention [5]. The basic idea of FCS-MPC is as follows.

(1) Use the predictive model of the control system to predict the control variables.

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(2) The cost function is used to represent the desired control system behaviour.

(3) The optimal control mode is determined by minimizing the cost function.

A state space model can be used to predict the state of a discrete-time system.

$$x(k+1) = Ax(k)+Bu(k) \tag{4}$$

$$y(k) = Cx(k)+Du(k) \tag{5}$$

Here, $x(k)$ represents the system state variable; $u(k)$ represents the system control variable; $y(k)$ represents the system output variable.

In the FCS-MPC strategy, the cost function g needs to be constructed to represent the control objective of the control system. The function needs to take into account the reference value and the reference variable of the control system. Let the system reference value be $y^*(k)$, then,

$$g_i = \left(y^*(k) - y_i(k)\right)^2 + \sigma f(u_i) \tag{6}$$

Where the first term is the square of the error between the control variable of the control system and its reference value. The second term is the constraint function $f(u_i)$ for the additional term of the control system, and the coefficient $\sigma$ is its weight coefficient. The weight coefficient can be adjusted to adjust the weight between the reference tracking and the control action. The control variable $u_{\min}$ that minimizes g is chosen to be applied to the control system at time $k$.

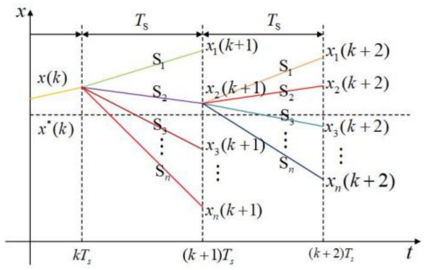


*Figure 2: Schematic diagram of finite control set model predictive control*

The basic principle is shown in Fig. 2, $T_s$ represents the sampling period of the control system, and the state variable of the control system at time $kT_s$ is $x(k)$. All the voltage vectors of the system are controlled for prediction at time $s_{kT}$, and $n$ different switching states are obtained as $S_k$ by corresponding to n different voltage vectors. It can be seen from Fig. 2 that at the $s_{kT}$ sampling time, the switching states 2 is closest to the reference vector $x^*(k)$, so $S_2$ is selected at the $kT_s$ sampling time. Similarly, $S_3$ is chosen at sampling time $(k+1)$ Ts; in this way, the execution is repeated for each sampling period.

When applied in power electronics, FCS-MPC control algorithms typically employ ergodic optimization methods. All the combinations of switching states are defined in advance before the start, and then the optimal switching state is selected to act on the power switch tube by the cost function judgment.

## 3. Implementation of FCS-MPC control strategy for grid-connected inverter

The FCS-MPC control structure established from the predictive current control model of the three-phase grid-connected inverter model is shown in Fig. 3. The load currents $i_a$, $i_b$ and $i_c$ are measured at time $k$, and the grid voltages $e_a$, $e_b$ and $e_c$ are transformed into $i_{\alpha\beta}(k)$, $e_{\alpha\beta}(k)$, $i_\alpha(k+1)$ and $i_\beta(k+1)$ through the three-phase stationary *abc* coordinate system to the two-phase stationary αβ coordinate system. $i_\alpha(k+1)$ and $i_\beta(k+1)$ are the currents in the two-phase stationary coordinate system predicted by the control algorithm. $i^*_\alpha(k+1)$ and $i^*_\beta(k+1)$ are the current reference values in the two-phase stationary coordinate system. The cost function is used to judge the current prediction value, so as to select the best switching state combination. $S_a$, $S_b$ and $S_c$ to control the power switch tube on and off.

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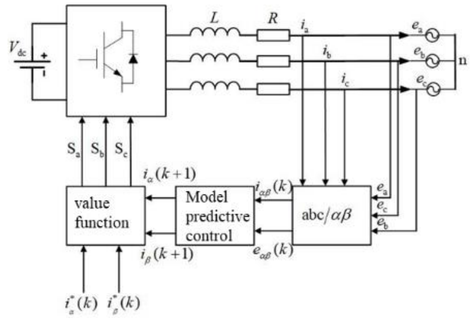


*Figure 3: Grid-connected inverter FCS-MPC control structure diagram*

According to the structure diagram shown in Figure 3, the control algorithm is designed step by step, and its implementation steps are as follows.

(1) Firstly, the grid side currents $i_a$ ,$i_b$ *and* $i_c$ are sampled, and the grid voltages $e_a$ ,$e_b$ *and* $e_c$ are transformed from the three-phase stationary *abc* coordinate system to the two-phase stationary αβ coordinate system into $i_\alpha(k)$, $i_\beta(k)$, $e_\alpha(k)$ *and* $e_\beta(k)$.

(2) Enter a loop statement, to predict the current at the next sampling time, and obtain $i_\alpha(k+1)$ *and* $i_\beta(k+1)$.

(3) $i^*_\alpha(k+1)$ *and* $i^*_\beta(k+1)$ are the given current reference values.

(4) The cost function is quadratic value form, namely the quadratic value of the difference between the current measurement value and the current reference value. The optimal voltage vector at this time can be judged by the minimum value of the cost function, and the corresponding switching state combination is the best.

(5) The best switching state combination is applied to the power switch tube.

(6) Wait for the next sampling period and repeat.

The cost function is given in equation (7),

$$g = \left(i^*_\alpha(k+1) - i_\alpha(k+1)\right)^2 + \left(i^*_\beta(k+1) - i_\beta(k+1)\right)^2 \tag{7}$$

According to the above analysis, the algorithm flowchart of FCS-MPC is shown in Fig 4.

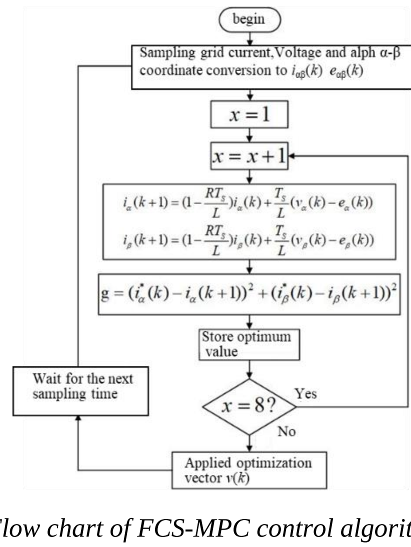


*Figure 4: Flow chart of FCS-MPC control algorithm flow chart*

## 4. Simulation verification

To verify the feasibility and effectiveness of the FCS-MPC control strategy, a simulation model of the LC filter type inverter system is built in MATLAB/Simulink. The conventional FCS-MPC control strategy is simulated with the same system simulation parameters as listed in Table 1.

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*Table 1 Simulation parameters of the inverter*

| Parameter names | Parameter values |
|---|---|
| Dc voltage $V_{dc}$ / V | 540 |
| The grid-connected voltage$e$ / V | 220 |
| The grid-connected frequency is $f$ / Hz | 50 |
| The reference current is$i^*$ / A | 20 |
| The reference current frequency is $f$ / Hz | 50 |
| Filter inductor equivalent resistance $R$ / Ω | 0.1 |
| The filter inductor $L$ / mH | 10 |
| The sampling frequency is $f_{sw}$ / kHz | 20 |

### 4.1 Simulation modelling and construction

In order to verify the effectiveness of the proposed FCS-MPC method for LC filtered inverters, an experimental platform is constructed as shown in Fig. 5 of A, and a detailed experimental study is conducted. The platform includes Typhoon602+ emulators and PE-Expert4 controllers. Where the control is performed on a PE-Expert4 processor board, which consists of a Digital Signal processor (DSP) and a Field Programmable Logic Gate Array (FPGA) chip.

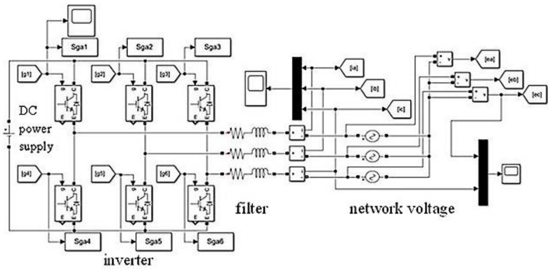



*Figure 5 Main circuit simulation model*

### 4.2 Dynamic performance of FCS-MPC

In order to verify the effectiveness of the proposed control method, we experimentally investigate the dynamic performance of the FCS-MPC method. In the experiments, the coefficients a and b in the proposed method are set to 416 and 5000, respectively.

When the reference voltage increases rapidly from 220 V to 250 V, Figure 6 shows the dynamic experimental results of the FCS-MPC method under the condition of parameter matching, where λ is the percentage of the current harmonic amplitude to the fundamental wave. AF is the fundamental current amplitude; $\lambda_{THD}$ is the total harmonic distortion rate.

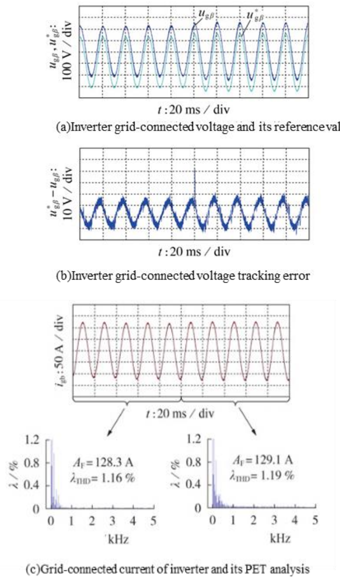
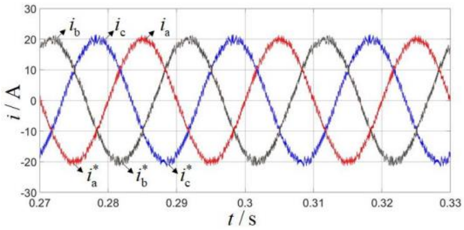



*Figure 6: Dynamic experimental results of FCS-MPC method when parameters match*

Based on Fig. 6, it can be seen that the FCS-MPC method produces a slight steady-state error and an elevated control accuracy, which is consistent with the theoretical analysis. In addition, the FCS-MPC method can quickly respond to a given value shift when the reference value of the grid connection voltage changes from 220 V to 250 V. (In the case of parameter mismatch L=0.0012 H, C=0.000 1 F and a=632, b=7 500 under the FCS-MPC method) dynamic process, as shown in Table 1, the dynamic voltage peak-to-peak error generated by the proposed FCS-MPC method is tiny, indicating that it has better dynamic performance.

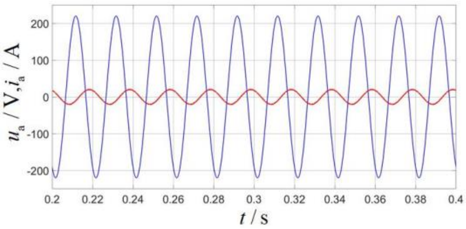
### *4.3 Steady-state performance of FCS-MPC*

The stable performance of a three-phase grid-connected inverter is an essential metric for measuring control algorithms. Figure 7 shows steady-state simulation waveform of grid-connected current for the FCS-MPC control strategy. Fig. 8 shows that the FCS-MPC control strategy tracks the reference current well.




*FCS-MPC*

*Figure 7: Steady-state simulation waveform of grid-connected current*




*FCS-MPC*

*Figure 8: FCS-MPC control strategy tracking current*

Figure 8 shows the simulated waveforms of the a-phase voltage $u_a$ and $i_a$ on the AC side of the inverter

## 5. Conclusion

In summary, the finite control set model has a excellent predictive control effect in the practical application process, and can be flexible applied to LC filter inverter. It overcomes the problems such as additional distortion in the traditional calculation process, and increases the speed of the whole power grid phase tracking.

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